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The improvement of CO_2 emission reduction policies based on system dynamics method in traditional industrial region with large CO_2 emission

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HIGHLIGHTS

- ► We build EECP model for CO_2 emission reduction study in traditional industry region.
- ► By the model, we simulate CO_2 emission trend and improve emission reduction policy.
- ► By improvement, both CO_2 emission intensity and economic cost can be largely reduced.
- ► Besides CO_2 emission is reduced effectively, higher GDP increment speed is kept.
- ► EECP model can be widely used for making and improving regional energy policies.

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ABSTRACT

Some traditional industrial regions are characterized by high industrial proportion and large CO_2 emission. They are facing dual pressures of maintaining economic growth and largely reducing CO_2 emission. From the perspective of study of typological region, taking the typical traditional industrial region—Liaoning Province of China as a case, this study establishes a system dynamics model named EECP and dynamically simulates CO_2 emission trends under different conditions. Simulation results indicate, compared to the condition without CO_2 emission reduction policies, CO_2 emission intensity under the condition of implementing CO_2 emission reduction policies of "Twelfth Five-Year Plan" is decreased by 11% from 2009 to 2030, but the economic cost is high, making the policies implementation faces resistance. Then some improved policies are offered and proved by EECP model that they can reduce CO_2 emission intensity after 2021 and decrease the negative influence to GDP, realizing the improvement objects of reducing CO_2 emission and simultaneously keeping a higher economy growth speed. The improved policies can provide reference for making and improving CO_2 emission reduction policies in other traditional industrial regions with large CO_2 emission. Simultaneously, EECP model can provide decision-makers with reference and help for similar study of energy policy.

1. Introduction

As the global climate change intensifies, the study of regional CO_2 emission especially the policy and method of CO_2 emission reduction has attracted worldwide attention. A lot of scholars have made massive research work, such as the relation between economic development and CO_2 emission (Choi et al., 2010; Ghosh, 2010), the influence of energy structure and CO_2 emission(Ross Morrow et al., 2010), the analysis of regional CO_2 emission trend (Peters et al., 2010), the summarization of regional CO_2 emission measures(Chicco and Stephenson, 2011)and so on. According to these studies, it can be found that the regional CO_2 emission is a complex system problem, which involves human activity, economy development, energy structure, policy orientation and other factors, as well as the long-term dynamic changes of these factors (Lozano and Gutiérrez, 2008).The formulation and improvement of regional CO_2 emission reduction policy should be studied by hanging on to the integrated and dynamic effects of regional economy, ecology, resource and society. Therefore, we need to start from the systemic viewpoint to integrate each main influencing factor, analyze the interaction of each factor, determine the regional CO_2 emission behavior and its long-term trend, and finally make the regional sustainable CO_2 emission reduction policy. However, currently the study of CO_2 emission reduction policy from the perspectives of system, dynamics and the combination of each factor is relatively few.

In the existing studies, some scholars always take some countries as examples to analyze CO_2 emission (Hammond and Norman, 2011; Sheinbaum et al., 2011). For instance, Park et al. (2010) used

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energy-environment models to analyze CO_2 emission and its reduction potential in Korean; Chen and Chen (2011) from supra-national scale analyzed the CO_2 emission characteristics in G7, BRIC and other countries. However, it should be paid attention that study of CO_2 emission from the national angle tends to make regional difference become average and comprehensive, and become difficult to reveal the key problems of regional CO_2 emission reduction. Since many countries are composed of regional units with different development characteristics, and their CO_2 emission reduction policies cannot be generalized. Some scholars also make research from the perspective of microscopic region (Finco and Doppler, 2010; Ruth et al., 2010), typically for example, Zhao et al. (2010) used LMDI method to analyze the influencing factors of industrial CO_2 emission in Shanghai, and he thought that the decline in energy intensity and the adjustment of energy and industrial structure are major determinants for reduction of industrial CO_2 emission in Shanghai. These studies have strong pertinence and cannot be widely applied for reference in other regions.

Therefore, in order to effectively improve the global problem, the academia should attach importance to the study from the perspective of typological regions. These regions have similar characteristics and great influence to global CO_2 emission. Therefore, choosing the typical case, using the systemic and dynamic analysis method, making or improving CO_2 emission reduction policy and summarizing the widely applicable model and method will have important theory significance and practical application value.

Traditional industrial regions with large CO2 emission are the areas with long industry-based development history and rapid development economy. Characterized by large consumption of resource, large emission of greenhouse gas and large energy consumption per GDP, these regions are widespread in the world especially in the countries with rapid development. They are important driving force of rapid development of regional or national economy, but simultaneously are main source of CO_2 emission and fossil energy consumption. Traditional industrial regions are facing dual pressures of maintaining sustained economic growth and largely reducing CO2 emission. Therefore, to a large extent, the problems of CO_2 emission and energy development in traditional industrial regions with large CO_2 emission can represent the highlighted contradictions and difficulties of CO_2 emission reduction in recent world. They should be paid full attention by academia and may become important study objects in future.

China has the largest annual CO_2 emission all over the world from 2006 (Guan et al., 2009).Liaoning Province with long history of industrial development, rapid economic growth, large consumption of coal-based fossil energy and high CO_2 emission is the typical representative of Chinese traditional industrial regions. To a large extent, it can reflect intensively the CO_2 emission characteristics in China, and even in traditional industrial region with large CO_2 emission in many other countries especially the developing countries.

Therefore, from the systemic point of view and taking regional economy, energy, CO_2 emission and policy as a whole, the study establishes EECP (Economy–Energy–CO_2 emission-Policy) model using system dynamics method, simulates and predicts the possible CO_2 emission trend of Liaoning Province in the future, then makes the targeted improvement policies of CO_2 emission reduction according to the characteristics of traditional industrial regions with large CO_2 emission. This study has important theory significance and practical reference value in predicting CO_2 emission trends, analyzing CO_2 emission reduction potential, and making or improving the energy development policies and CO_2 emission reduction policies which meet regional development requirement in other traditional industrial regions with large CO_2 emission all over the world.

2. Study area

Liaoning Province (118°53′–125°46′E, 38°43′–43°26′N) is located in the northeast of China (Fig. 1), and has a continental temperature monsoon climate. The annual solar radiation is between 100 and 200 cal per square centimeter; the annual average sunshine is between 2100 and 2600 h; the annual average temperature is between 7 °C and 11 °C; the annual average frost-free period is between 130 and 200 days, increased gradually from the northwest to the southeast; the annual average rainfall is between 600 and 1100 mm; the land area is 145,900 square kilometers which accounts for 1.5% of Chinese total land area; the total population at the end of 2009 is 4256 million which accounts for 3.19% of Chinese total population.

2.1. Rapid development of regional industrial economy

With the rapid economic development in Liaoning Province in recent years, the annual average GDP was increased by 17.99% from 2005 to 2009, and in 2009 the GDP was amounted to 1.52125 trillion Yuan (the unit of Chinese currency, 1 Yuan= 0.153808 dollar (the exchange rate on 28th, April)) which was increased by 11.3% as against 2008 and accounting for 4.43% of the total GDP of china. Therefore, Liaoning Province becomes one of the most important provinces, which can promote the economic development around Bohai Sea and even in China. Since the foundation of the People's Republic of China, Liaoning has been dominated by industry in the economic system and has become the famous old industrial base. In 2009, the economical contribution rate of the secondary industry accounted for 60.7%, of which industry accounted for 50%.

2.2. Large consumption of fossil energy

High industrial proportion and rapid economic development in Liaoning Province has brought large energy demand. In 2009, the total energy consumption reached 191.1 million tons SCE(standard coal equivalent); hydropower and other non-fossil energy consumption accounted for less than 1% of total energy, while fossil energy consumption accounted for more than 99%, of which coal energy consumption accounted for 76.5% (Fig. 2).

In recent years, Liaoning Province attaches importance to the investment of science and technology and constantly improves technological level of industrial development, making energy

Fig. 1. The location map of Liaoning Province.

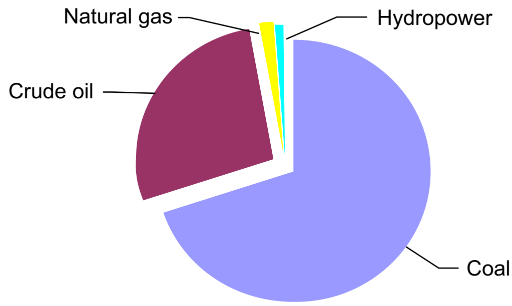

Fig. 2. Primary energy consumption structure in Liaoning Province.

Table 1
The energy consumption per GDP in some countries in 2008.(tons SCE per thousand dollars).

countries	energy consumption per GDP	countries	energy consumption per GDP
China	0.463	America	0.162
Japan	0.103	England	0.08
Germany	0.085	France	0.09
Italy	0.077	Australia	0.117

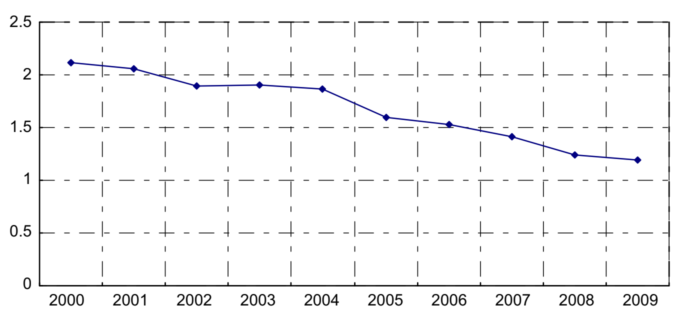

Fig. 3. Energy consumption per GDP in Liaoning Province.

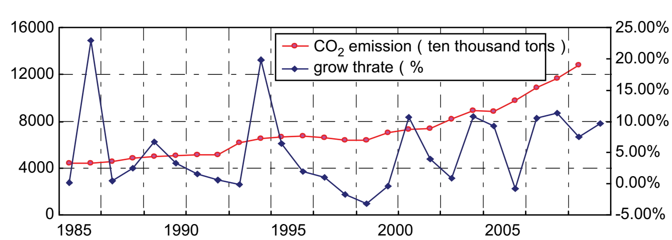

Fig. 4. The amount and growth rate of CO_2 emission in Liaoning Province.

consumption pre GDP decrease year by year. However, compared with industrial technology in developed areas, the industrial technology in Liaoning Province is still relatively laggard and its development mode is relatively extensive. In 2008, the energy consumption per GDP of Liaoning province is amounted to 1.3 t SCE per ten thousand Yuan, which is 0.8 t SCE per thousand dollars, much more than that of developed countries (Table1) (Fig. 3).

2.3. Gradual increase of CO_2 emission

Rapid economic growth makes energy demand increase, and more and more consumption of fossil fuel leads to a continuous rise of CO_2 emission. From 1985 to 2009, CO_2 emission was increased continuously from 44.3 million tons to 128.2 million tons at an annual average growth rate of 5.2%, especially after 2005, with the accelerated development of economy, the annual average growth rate of CO_2 emission reached 7.6% (Fig. 4).

3. The framework design of CO_2 emission reduction policy

Fossil fuel burning is the main source of CO_2 emission caused by human economic activity in traditional industrial areas with large CO2 emissions, and simultaneously reducing the fossil fuel burning is probably the key process of CO_2 emission reduction. Therefore, taking economy, energy and CO_2 emission as a whole system, this study uses "GDP", "energy consumption", "annual CO_2 emission amount" and other corresponding indicators to reflect economy, energy and CO_2 emission, analyzes their interaction relations and internal material flow, summarizes the control factors of each indicator and finally designs the framework of CO_2 emission reduction policy as follows (Fig. 5):

(1) Through executive order, government subsidy, fine and other measures, government should accelerate the elimination of laggard production capacities with large energy consumption, high emission and low yield. On one hand government should control the overquick economic growth and keep the economic development appropriate and reasonable; on the other hand government should decrease energy consumption per GDP so as to reduce CO_2 emission.
(2) Through direct investment, special subsidy establishment and so on, government should increase the investment in energy-saving technology and improve production technology to enhance energy efficiency and reduce energy consumption per GDP. (3) Through direct investment in infrastructure construction, low-interest loan, tax exemption, cheap land and other policies for relevant companies, government should fully develop non-fossil energy and reduce the proportion of fossil energy.

The framework of CO_2 emission reduction policy can well reflect the function pathways of emission reduction measures, and can provide good theoretical basis for prediction of regional CO_2 emission trend, formulation of CO_2 emission reduction policies and quantitative analysis of implementation effects.

4. Model and data

4.1. System dynamics model

The system dynamics method was created by Professor Forrester of Massachusetts Institute of Technology in the mid-1950 s (Forrester, 1958). After decades of development and improvement, the systemic dynamics model has been widely used in the study of economy, society, ecology and many complex systems (Aghdam, 2011; Kiani and Ali Pourfakhraei, 2010; Pathapati et al., 2005). The systemic dynamics model can reveal the dynamic changes, feedback, delay and other processes of a system, and it is characterized by quantifiability and controllability. Therefore, it has a distinct advantage in analyzing, improving and managing the system characterized by long development cycle and complex feedback effects (Naill, 1992).Therefore, the systemic dynamics method meets the modeling requirement in our study.

4.2. Data resource

The data used in this model mainly comes from "1978–2010 Statistical Yearbook of Liaoning Province", "Chinese Energy Statistics Yearbook", the internal information provided by Liaoning

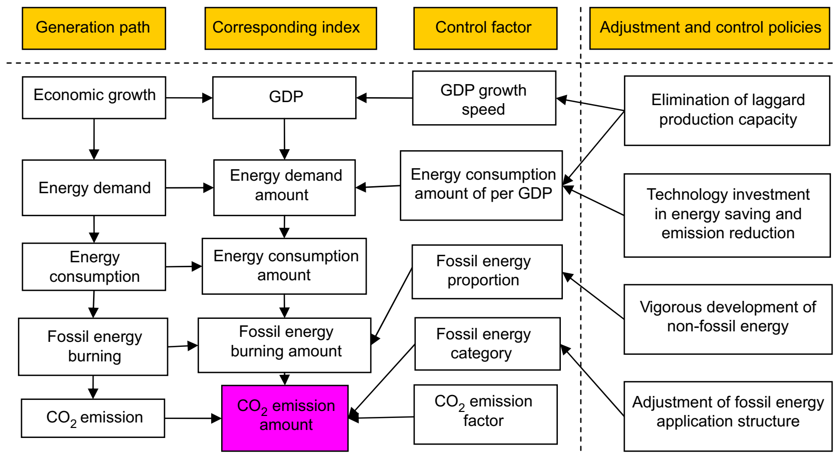

Fig. 5. The framework of CO_2 emission reduction policies.

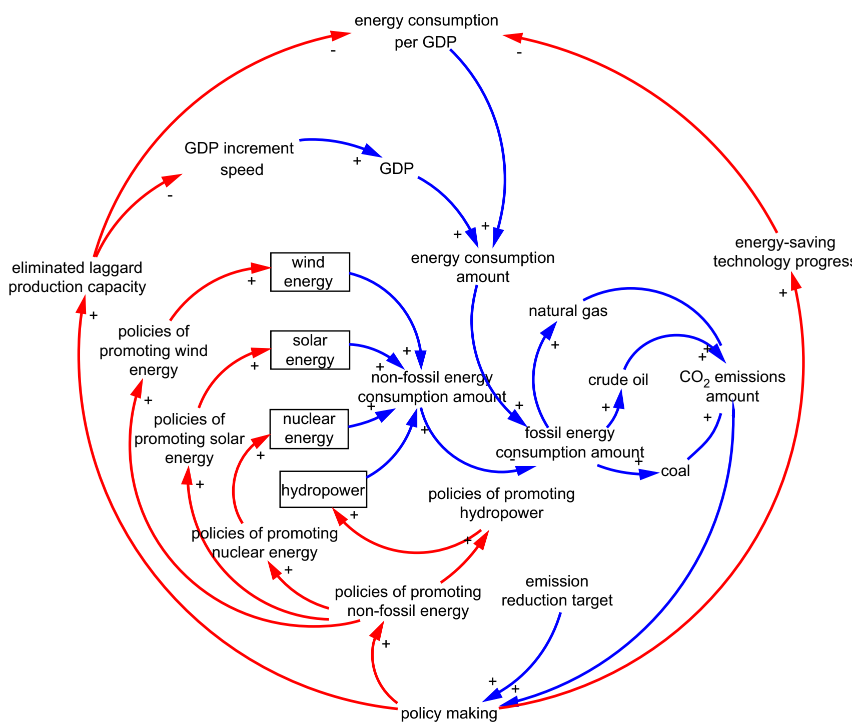

Fig. 6. The causal loop framework of EECP model.

government, questionnaires from field investigation into relevant enterprises and so on. The energy conversion coefficient and CO_2 emission factors in the model mainly base on the standard of “Chinese Energy Statistics Yearbook” and “2006 IPCC Guidelines for National Greenhouse Gas Inventories”.

In addition, the fossil fuel consumed by human activities all comes from primary energy. Therefore, we only analyze the total amount of regional primary energy consumption which can include all the energy consumption caused by human activities in the study.

5. The modeling process

According to the framework of CO_2 emission reduction policies, we build a system dynamics model named EECP (Economy–Energy–CO_2 emission-Policy) to simulate the dynamic evolution of the economy development, energy consumption and CO_2 emission, and then improve the CO_2 emission reduction policy.

5.1. Causal loop framework

According to the quantitative indicators and causal loop relationships in the framework of CO_2 emission reduction policy, the causal loop framework is designed (Fig. 6).

GDP growth makes the total energy demand and consumption increase, and then causes the increase of fossil energy consumption and CO_2 emission amount. Through the comparison between the actual CO_2 emission and the CO_2 emission reduction target, the corresponding policies can be made and the implementing way can be determined. The processes of CO_2 emission and CO_2 emission reduction policies making are shown by the blue arrows in Fig. 6. CO_2 emission reduction policies may include eliminating the laggard production capacity with large energy consumption and high emission, promoting the improvement of energy-saving technology, decreasing energy consumption per GDP and increasing the proportion of non-fossil energy consumption. The processes of polices adjustment and control are shown by the red arrows in Fig. 6.

5.2. Stock-flow diagram

Stock-flow diagram is the core of EECP model and is the process of quantization and materialization of causal loop framework. According to causal loop framework of EECP model, the stock-flow diagram is built by using VENSIM software which is composed of 7 level variables, 7 rate variables and 40 auxiliary variables (Fig. 7). The parameters and simultaneous differential equations in the stock-flow diagram are defined on the basis of the actual data for CO_2 emission from 1978 to 2008 in Liaoning Province

Since China has promised in Copenhagen meeting that CO_2 emission per GDP in 2020 should be reduced by 40–45% of that in 2005, meaning it should be reduced to 55%–60% of that in 2005. Therefore, in this diagram we hypothesize the emission reduction target 1 and target 2 respectively represents 60% and 55% of CO_2 emission in 2005 in Liaoning Province (the target is only used for model study, not the actual program).

According to the framework of CO_2 emission reduction policy, the policies are classified into two categories: one is adjustment policies about production capacity and technology, which control and influence the variables such as "the eliminated laggard production capacity" and "special investment in energy-saving technology"; the other is promotion policies about non-fossil energy development, which control and influence the variable such as "non-fossil energy development". Through policies adjustment, GDP increment, energy consumption per GDP and the total amount of non-fossil energy may gradually decrease, resulting in the decrease of fossil fuels consumption and CO_2 emission. The proportions of coal, oil and natural gas in primary fossil energy consumption are respectively expressed by P1, P2 and P3; their CO_2 emission factors are respectively expressed by e1, e2 and e3; their CO_2 emission amounts are respectively expressed by CO_2 emission 1, CO_2 emission 2 and CO_2 emission 3. The whole diagram constitutes a negative feedback loop of the CO_2 emission generation process and CO_2 emission reduction process.

5.3. Model testing and validation

Model testing and validation aim at justifying the reliability of the model and providing confidence for model application. System development from 2000 to 2009 is simulated and then the simulated result is compared with the historical actual data for energy and CO_2 emission. Result shows their fitting degree is more than 0.97 and the model meets simulation requirement. Through varying the parameter value from maximum to minimum, whether the simulated results of relevant variables accord with logic is tested. Result shows the relevant variables variations accord with the probable system variations under the extreme conditions, moreover, when the parameter varies, the simulation trends of relevant variables is not changed, proving the response of model to parameter variation is sensitive and in accord with logic. The model built is feasible and reliable.

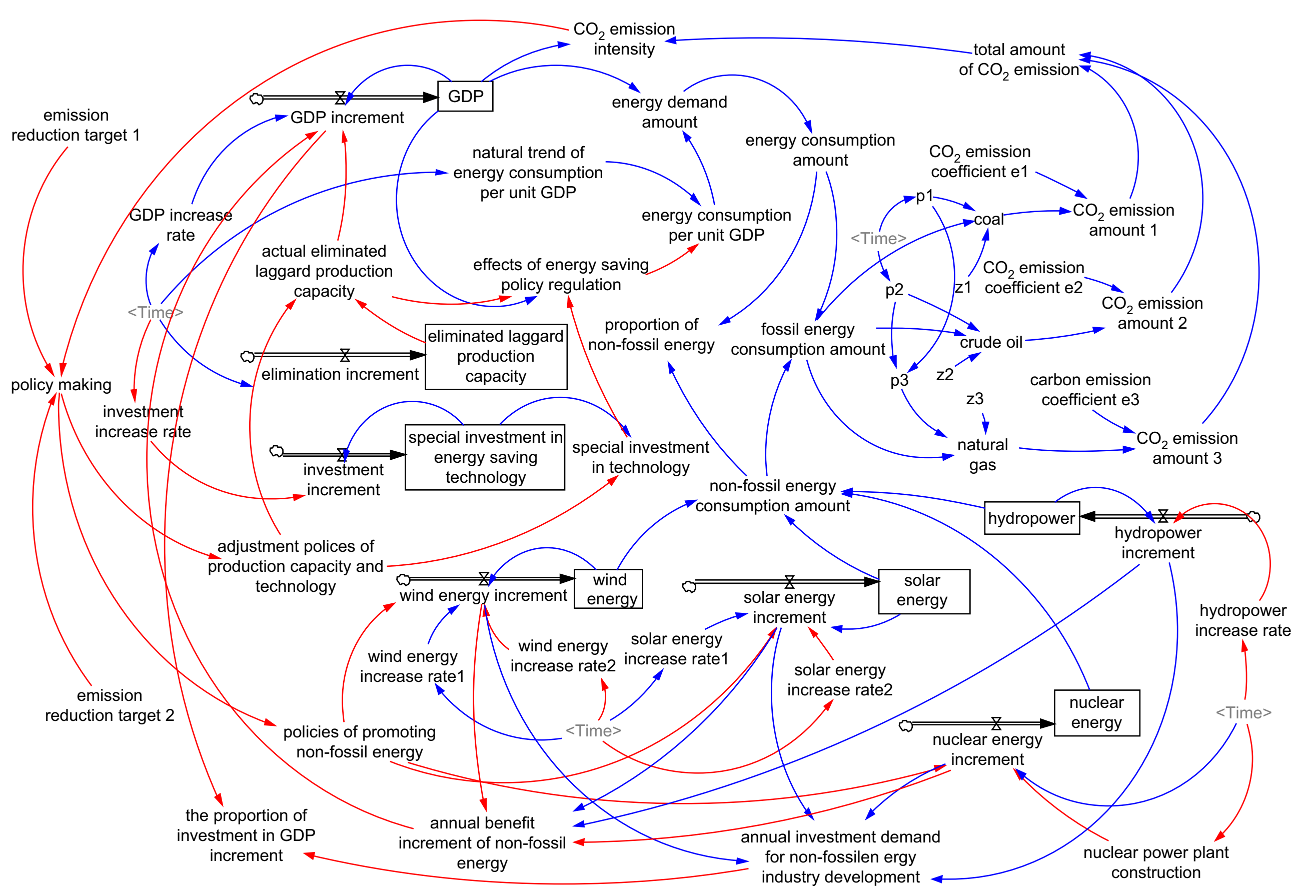

Fig. 7. The stock-flow diagram of EECP model.

6. Simulation of CO_2 emission trend in Liaoning province

Utilizing EECP model, we simulate and analyze the possible trend of CO_2 emission from 2009 to 2030 in Liaoning Province, then make and improve relevant policies of future energy development and CO_2 emission reduction in order to achieve the maximization of CO_2 emission reduction and the sustainable development of regional economy.

6.1. CO_2 emission simulation under the condition without emission reduction polices

By utilizing EECP model, CO_2 emission in Liaoning Province in the future is simulated under the condition without emission reduction polices of energy-saving policies. The simulation process is named "WP mode". China always draws up a new plan of economic and social development every five years and now is the ending of "Eleventh Five-Year Plan" and the beginning of "Twelfth Five-Year Plan". Therefore, simulation of future CO_2 emission trend under the condition without emission reduction polices can provide a good contrast reference for the simulation results of different conditions.

As the traditional industrial region with large CO_2 emission, Liaoning province has attached great importance to relevant study of energy-saving technology and emission reduction measures since 2000 according to the economic development realities. Over many years, Liaoning Province has developed and implemented a series of measures such as the elimination of laggard production capacity basing on the characteristics of high proportion of industry and large consumption of coal and other fossil energy, and combining with the Chinese government' energy saving plan. Under the effect of these measures, although the total amount of energy consumption and CO_2 emission were still rising from 2005 to 2009 in Liaoning Province, the rising speed obviously slowed and the annual average fossil energy consumption increment decreased 500 million tons, equivalently reducing great amounts of CO_2 emission. Liaoning Province had become one of the pioneers in the activities of energy saving and emission reduction in China.

Simulation shows, if new policies for energy-saving and emission reduction are not implemented after 2010, meaning under the "WP mode" scenario, CO_2 emission of Liaoning Province may continuously increase with the rapid growth of GDP. To 2030, GDP of Liaoning Province may reach 8264.9 billion Yuan; the CO_2 emission intensity may reach 1.7 t per ten thousand Yuan; due to technological progress and natural upgrading of industry, energy consumption per GDP in Liaoning Province may gradually decrease to 0.7 t SCE per ten thousand Yuan, but the rapid growth of GDP may still make CO_2 emission rapidly increase to 1.4 billion tons, resulting in huge negative ecological effects. (Fig. 8).

Meanwhile, although non-fossil energy may develop rapidly, its proportion in total energy consumption may be still small, because there is no adjustment and control about energy-saving policy and the fossil energy consumption may increase more rapidly. In 2003 the proportion of non-fossil energy only rose to 1.9% due to the establishment of Hongyanhe nuclear power plant, but then may gradually decline to 0.9% to 2030 (Fig. 8).

7. CO_2 emission simulation under the effect of "Twelfth Five-Year Plan" policies

7.1.1. Scenario hypothesis

During the period of "Twelfth Five-Year Plan" (from 2011 to 2015), Liaoning Province enhances the effort for energy saving and emission reduction, and clearly puts forward the programs and goals of non-fossil energy development. Meanwhile, according to Chinese government's plan about eliminating laggard production capacity, in next five years, the eliminating laggard production capacity, energy-saving technology and energy-saving projects are listed.

According to the contents of "Twelfth Five-Year Plan", the CO_2 emission trend in Liaoning Province under the effect of "Twelfth Five-Year Plan" policies is simulated by utilizing EECP model, and the simulation process is named "12.5 plan". Since the parameters settings all base on the planning documents issued by Liaoning province government, the simulation result are closest to the future real CO_2 emission trend in Liaoning Province.

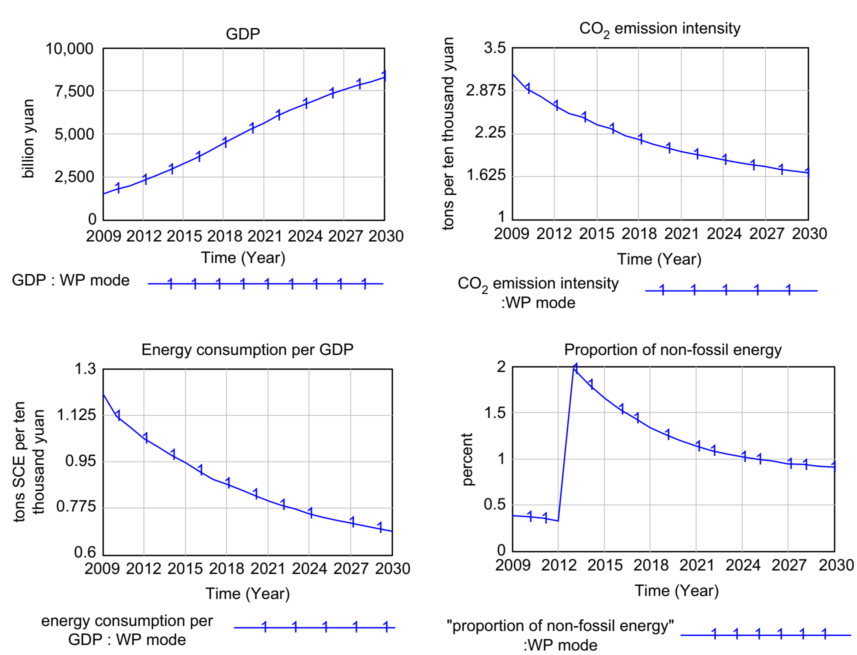

Fig. 8. CO_2 emission of "WP mode" scenario.

This study dynamically simulates and comparatively analyzes every parameter change of "12.5 plan" and "WP mode" scenario, identifies the benefits and defects of CO_2 emission reduction of "12.5 plan", analyzes the possible potential of CO_2 emission reduction and then makes improvement policies.

8. Analysis of simulation results of "12.5 Plan"

8.1. The effect of adjustment of production capacity and technology

In the future, Liaoning Province will implement the policies of eliminating laggard production capacity in a long time and will strengthen investment in key projects of energy saving and emission reduction. According to the list of eliminating laggard production capacity and the "First Batch Directory of Technology of Energy-Saving and Emission Reduction in Liaoning Province" issued by Liaoning Province government as well as the relevant field research data, the parameters about eliminating laggard production capacity and special investment in energy-saving technology are defined in the EECP model by VENSIM software. So that, the research group can calculates the eliminated production capacity. (The specific definition of variables and equations in VENSIM software are listed in the appendix table).

Simulation results indicate that, under the effect of "Twelfth Five-Year Plan" policies, the economic losses coming from production capacity elimination may exceed 1/3 of GDP increment in Liaoning Province in 2020. Therefore, it is difficult to continue implementing the policy of eliminating laggard production capacity to ensure sustained economic growth. Meanwhile, after 15-year policies implementation of production capacity and technology, large-scale elimination of laggard production capacity and technology investment may be limited, because if the policies continue being implemented, the cost may likely exceed the benefits gained. Therefore, the implementing deadline is defined at 2020 in the model. According to this hypothesis, to 2020 the eliminating production capacity may reach the maximum of 124.8 billion Yuan, and the special investment in technology may reach 10 billion Yuan. These two policies may be no longer carried out from 2021 (Fig. 9)

8.2. The effect of promotion of non-fossil energy development

The non-fossil energy industry in Liaoning province has good development foundation and potential: **Wind energy:** Liaoning Province has abundant wind energy resource. the annual average wind speed is more than 3.5 m/s; the annual average wind power density is more than 100 w/m^2; the area of available wind energy regions where the annual effective wind hour is more than 5000 h accounts for 1/2 of total area, of which the area of coastal, northern and central wind-rich regions with annual average wind speed of 4.5 m/s, annual average wind power density of 150 w/m^2 and annual effective wind time of 6000 h accounts for 1/3. Moreover, Liaoning Province has abundant wind energy resource in Bohai Sea and great development potential for wind energy resource.

Nuclear energy: Nuclear power utilization of Liaoning Province is still in its infancy. The Hongyanhe nuclear power plant which is being built will be put into use at the end of 2012, and its installed capacity may reach 4 million kilowatts, planning to expand to 6 million kilowatts at the end of 2017; the programming Xudabao nuclear power plant is expected to complete at 2017 with the installed capacity of 2 million kilowatts.

Solar energy: Liaoning Province has abundant solar energy source. The annual average radiation is more than 5000 mj/m^2 and the available area of solar energy regions where the annual sunshine reaches 2600 h accounts for more than 1/2 of the total province area. However, due to the constraints of technology, application and investment costs, the utilization of solar energy is difficult to rapidly expand to a larger scale in the future.

Hydropower: The development potential of hydropower in Liaoning Province is smaller than other non-fossil energy, and currently it has been developed by 35% of total usable water resource in 2009. Hydropower can develop rapidly in the future, but due to the constraint of water resource, its development is relatively limited.

Since the Copenhagen meeting holding, Liaoning Province has attaches great importance to non-fossil energy development and clearly puts forward the goals of non-fossil energy development in the just released "Twelfth Five-Year Plan of economic and social development in Liaoning Province" basing on the development potential of non-fossil energy mentioned above. Specifically, in 2015, the installed capacity of nuclear power should reach 4.3 million kilowatts; the wind power capacity should reach 6 million kilowatts, striving to reach 10 million kilowatts; the photovoltaic generating capacity should reach 0.3 million kilowatts. According to these goals and the actual data of non-fossil energy development in Liaoning Province in recent years, the parameters of future non-fossil energy development is defined in the EECP model (appendix table).

Simulation results of "12.5 plan" scenario show that non-fossil energy in Liaoning Province may develop rapidly in the next 5 to 10 years. To 2020, the annual usage amount of wind energy, nuclear energy, solar energy and hydropower may respectively reach 22.8, 8.6, 1.1 and 1.0 million tons SCE, and then the total amount of non-fossil energy may reach 33.5 million tons SCE, accounting for 10.4% of the total energy consumption. To 2030, the annual usage amount of wind energy, nuclear energy, solar energy and hydropower may respectively increase by 32.2%, 100%,13.5% and 14.5%, and the total amount of non-fossil energy may reach 49.7 million tons SCE, 9.6 times of that of "WP mode" scenario (Fig. 10).

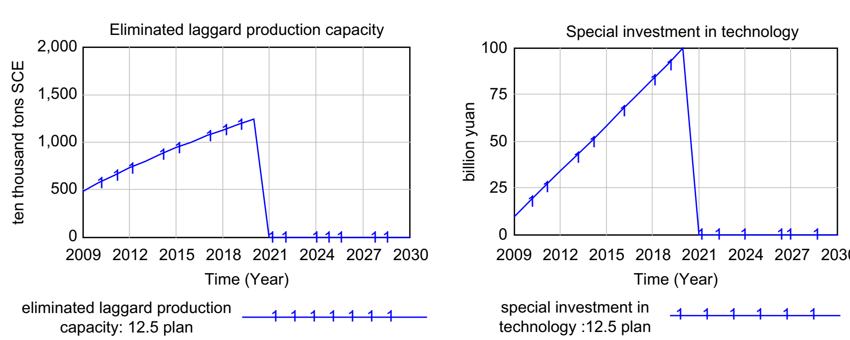

Fig. 9. The eliminating laggard production capacity and special investment in technology of "12.5 plan" scenario.

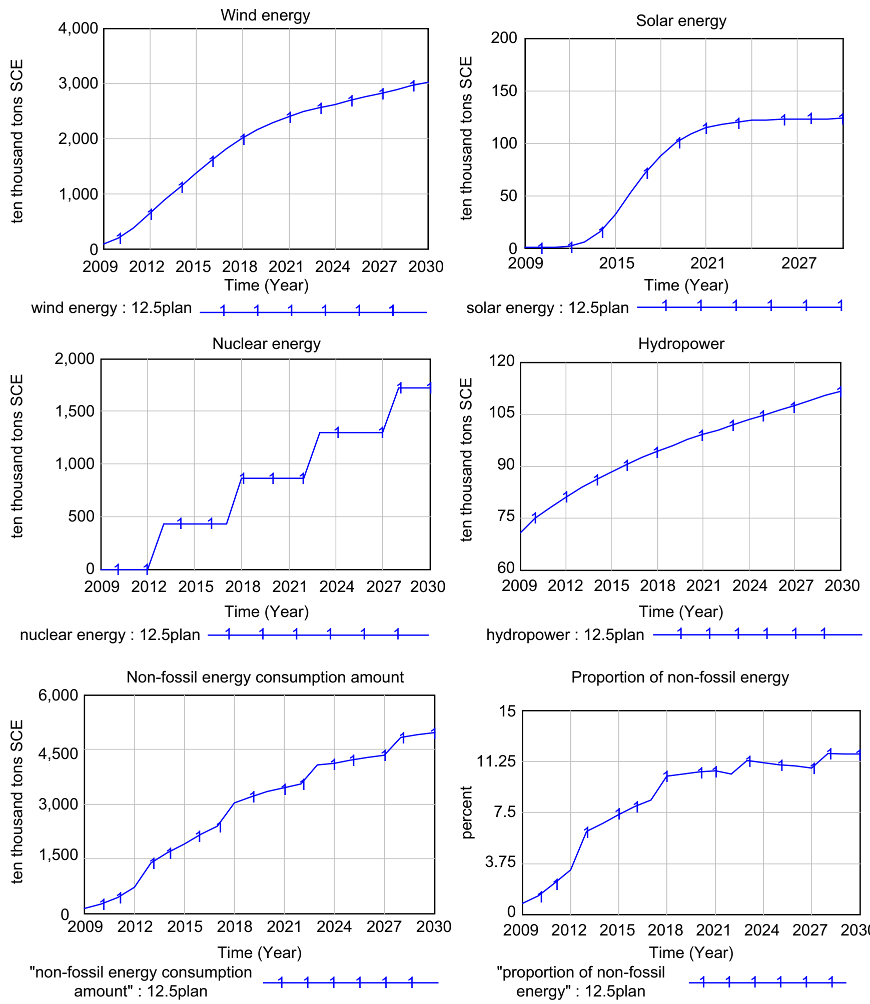

Fig. 10. Simulation of non-fossil energy development of "12.5 plan" scenario.

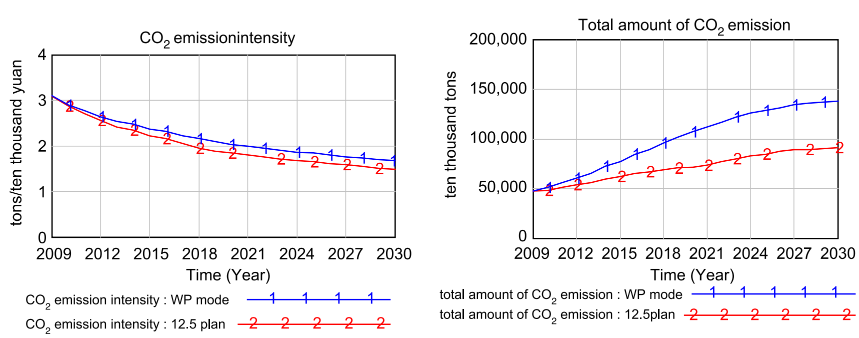

Fig. 11. Simulation of economic growth and CO_2 emission of "12.5 plan" scenario "improvement" scenario.

8.3. Economic growth and CO_2 emission

Through eliminating laggard production capacity, specially investing in technology and promoting non-fossil energy development, the future economic growth speed in Liaoning Province may gradually slow down. Compared with the "WP mode", economic growth of "12.5 plan" scenario tends to be more rational, and the economic development and environmental protection keep balanced. Although GDP growth speed may increase slightly to 2021 after abolishing these policies, its trend may decrease. To 2030, the total GDP in Liaoning Province may reach 6122.2 billion Yuan, 25.9% lower than that of "WP mode" scenario. (Fig. 11)

At the same time, the total amount of CO_2 emission and emission intensity may decrease significantly compared with "WP mode" scenario, and to 2020 the total amount of CO_2 emission in Liaoning Province may reach 718.4 million tons, 32.7% lower than that of "WP mode" scenario, and CO_2 emission intensity may reach 1.8 t per ten thousand Yuan, 10.1% lower than that of "WP mode" scenario. To 2030 the annual CO_2 emission in Liaoning Province may reach 910.4 million tons, 34% lower than that of "WP mode" scenario, and CO_2 emission intensity may reach 1.5 t per ten thousand Yuan, 11% lower than that of "WP mode" scenario. (Fig. 11) Compared with "WP mode" scenario, it can be seen that "12.5 plan" scenario can achieve much better effects of CO_2 emission reduction in Liaoning Province.

8.4. *Analysis of advantages and disadvantages of emission reduction policies in "Twelfth five-year plan"*

According to the simulation results of "12.5 plan" scenario by EECP model, the advantages and disadvantages of each emission reduction policy are analyzed as follows:

Firstly, eliminating laggard production capacity, specially investing in energy-saving technology, improving industrial technological level and other adjustment policies for production capacity and technology can rapidly reduce the energy consumption pre GDP and greatly decrease CO_2 emission. These are desirable CO_2 emission reduction policies in short time. However, as energy consumption per GDP continuously decreases, the economic loss from eliminating laggard production capacity may gradually increase and the effects of energy saving and CO_2 emission reduction may become not significant. To ensure sustainable growth of economy, these policies will be difficult to continue be implemented and the emission reduction effects cannot be maintained for a long time. Therefore, these policies are more suitable for short-term implementation, not for long-term promotion.

Secondly, currently the proportion of non-fossil energy consumption of Liaoning Province is less than 2% in the total energy consumption, and the technology, facility, applicable field, acceptance extent of people and other aspects about non-fossil energy industry are lacking. Especially as the radioactive material of Fukushima nuclear plant in Japan leaked, people have higher security requirement and keep more cautious attitude to nuclear plants development. Therefore, even if large capital investment in non-fossil energy is given in short time, it is difficult for non-fossil energy to expand rapidly to a large scale.

Moreover, the development of nuclear power plant, photovoltaic power plant and other non-fossil energy industries need large investment, long-term construction and high level technology, and it is difficult to recover costs and gain profit in short time. Therefore, large investment in non-fossil energy industries in short time may result in overlarge economic pressure, and it is difficult to continue investing, limiting the potential of the non-fossil energy proportion growth in the future. Therefore, this policy is more suitable for long-term implementation, not for short-term promotion. In order to lay a good foundation for comprehensive development of non-fossil energy industries in the future, recently it should be paid more attention to the production facility, talent introduction, technology upgrade, application development and related industries support about non-fossil energy industries.

Thirdly, although the implementation of emission reduction policies of "Twelfth Five-Year Plan" can largely reduce the environment pressure brought by rapid economic growth, they also cause greater economic costs. Therefore, it is necessary to appropriately improve these policies to decrease economic costs as possible on the premise of increasing CO_2 emission reduction benefits.

9. Improvement recommendations of CO_2 emission reduction policies in Liaoning province

According to the simulation results of "12.5 plan" scenario and "WP mode" scenario, CO_2 emission reduction policies in "Twelfth Five-Year Plan" are improved and adjusted. Through correcting relevant parameters in EECP model, the system under the effect of improved recommendations is simulated and the simulation process is named "improvement".

9.1. *Recommendations of policy improvement*

9.1.1. *Adjustment of production capacity and technology*

Taking reducing CO_2 emission per GDP by 40% to 45% of that in 2005 as the recent CO_2 emission reduction target, government should vigorously implement the policies of eliminating laggard production capacity and specially investing in energy-saving technology until achieving the target. Through executive orders, special subsidies, fines and other measures, government should accelerate the elimination of laggard production capacity with large energy consumption, high emission and low yield; through direct investment of financial grants, establishment of special subsidy and so on, government should increase technology investment in energy saving, new energy development and other relevant projects.

In the EECP model, we define respectively CO_2 emission intensity of 60% and 55% of that in 2005 as emission reduction target 1 and target 2 (that means CO_2 emission intensity is lower by 40% and 45% than that in 2005). When target 1 is achieved, the implementation force of adjustment of production capacity and technology can be halved; when target 2 is achieved, the policies adjustment can be stopped. Meanwhile, we also set up five-year grace period to ensure a smooth transition of implementation force change. This measure ensures the elimination process more smooth on the premise that the total elimination amount is unchanged, and decrease greatly the impact of policy change to economic system.

9.1.2. *Promotion of non-fossil energy development*

We suggest that government should decrease short-term investment in non-fossil energy before 2015, and moderately increase investment after 2020; halve the expected scale of nuclear plant in 2012; increase by 50% of existing nuclear power scale in 2022.

Based on the above recommendations, relevant parameters are adjusted in the EECP model, of which due to the constraint of

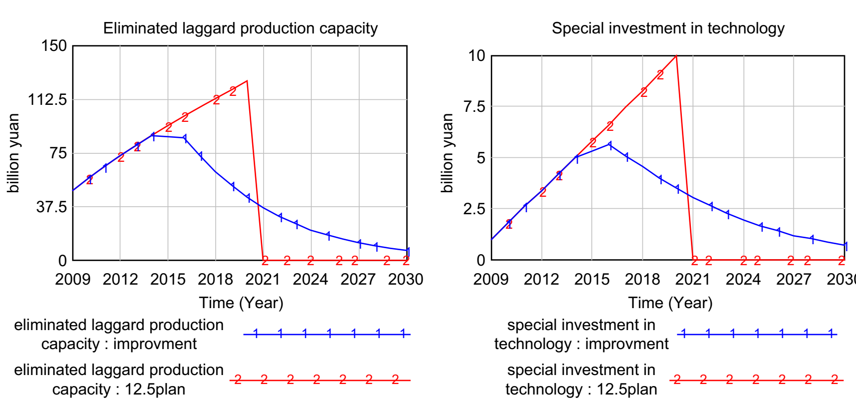

Fig. 12. The eliminated laggard production capacity and special investment in technology of "improvement" scenario.

water resource condition, hydropower parameters of "12.5 plan" scenario are remained.

9.2. CO_2 emission simulation under the effect of policies improvement

9.2.1. The effect of adjustment of production capacity and technology

CO_2 emission reduction of Liaoning Province is simulated under the effect of improved recommendations by the EECP model. Simulation results show that to 2016 CO_2 emission intensity of Liaoning Province may amount to 2.18 t SCE per ten thousand Yuan, lower than emission reduction target 1 and target 2 (2.42 and 2.22 t SCE per ten thousand Yuan) (Fig. 15), and eliminated laggard production capacity and special investment in energy-saving technology may gradually decrease to 0 in the grace period (Fig. 12). GDP growth speed is lower than that of "WP mode" scenario, but higher than that of "12.5 plan" scenario (Fig. 13). These results indicate to some extent, under the effect of improved recommendations, excessive CO_2 emission brought by rapid

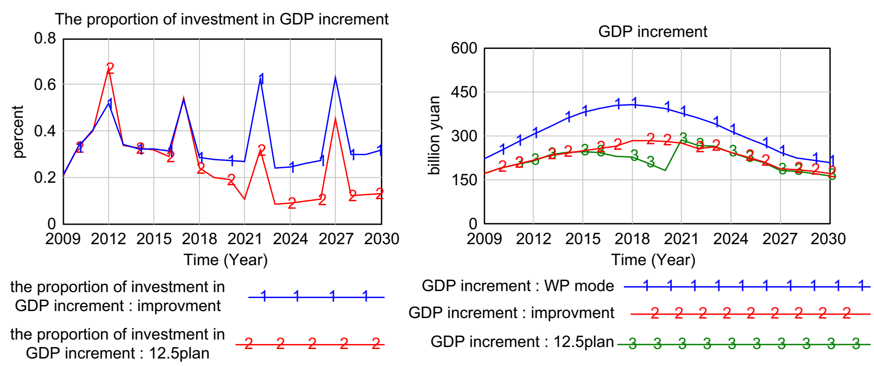

Fig. 13. The investment in non-fossil energy industries and GDP increment of "improvement" scenario.

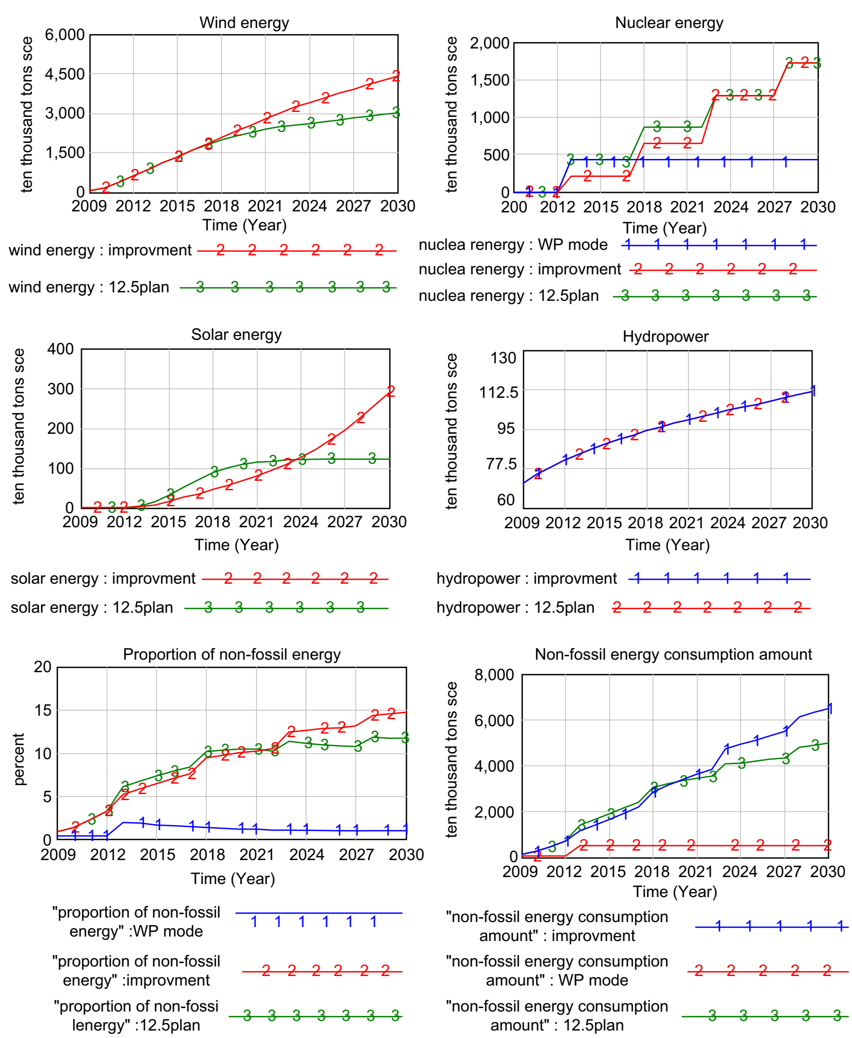

Fig. 14. Non-fossil energy development of "improvement" scenario.

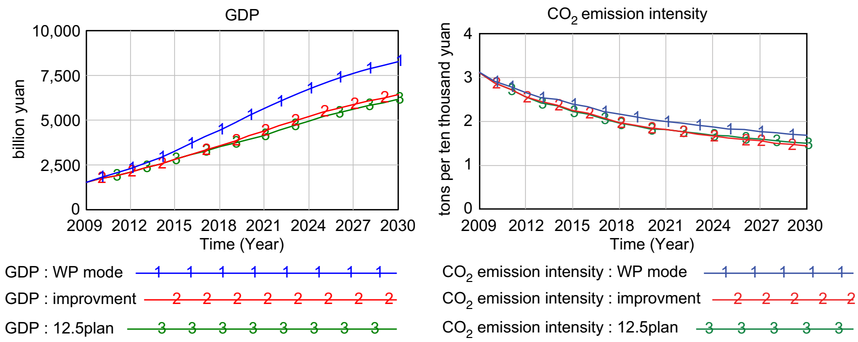

Fig. 15. Economy development and CO_2 emission of "improvement" scenario.

economic growth can be reduced, excessive economic costs can be prevented and the relatively stable growth of economy can be ensured (Fig. 12).

9.3. The effect of promotion of non-fossil energy development

Through the adjustment of investment time to non-fossil energy industries, in 2012, the investment proportion in GDP increment may decrease to 52%, compared to 67% of "12.5 plan" scenario. To 2022, it may increase to 62.5%, compared to 32% of "12.5 plan" scenario. Under the effect of this adjustment, on one hand, the short term economic burden of Liaoning Province can be reduced and the sustainable economic growth can be promoted; on the other hand, after 5–10 years development, the technology level, the acceptance of the populace and infrastructure construction of non-fossil energy industries will be improved greatly, and then expanding the investment in non-fossil energy not only can ensure the sufficient capital and high efficiency, but also can give full control to the driving role of industry to economy (Fig. 13).

Before 2020, the development of non-fossil energy of "improvement" scenario lags slightly that of "12.5 plan" scenario, but the gap gradually lessens after 2015. To 2020, the annual utilization amount of wind energy, nuclear energy, solar energy and hydropower in Liaoning Province may respectively reach 25.7 million tons SCE, 6.5 million tons SCE, 687 thousand tons SCE and 976.3 thousand tons SCE, and the total non-fossil energy may amount to 33.7 million tons SCE, exceeding that of "12.5 plan" scenario; to 2022, the proportion of non-fossil energy in total energy consumption may also exceed that of "12.5 plan", reaching 10.6% (Fig. 14). After that, the non-fossil energy industry may have a certain scale, its technology may be relatively mature, and then good economic benefits may be gained. At this time, enhancing the investment in the non-fossil energy industries is easier to obtain social and decision-makers' recognition. Through government's large-scale investment, non-fossil energy may rapidly develop and CO_2 emission reduction effect may become more obvious. Then to 2030, the non-fossil energy consumption may amount to 68.3 million tons SCE, 1.4 times of that of "12.5 plan" scenario and the proportion of the non-fossil energy may reach 15.5% in total energy consumption, increasing by 3.7% of that of "12.5 plan" scenario (Fig. 14).

9.3.1. Economic growth and CO_2 emission

Through the improved recommendations about production capacity, technology and non-fossil energy, the total CO_2 emission amount in Liaoning Province is slightly higher than that of "12.5 plan" scenario after 2013, but the gap gradually lessens after 2021. To 2028, the regional total CO_2 emission amount may decrease to 89 million tons, lower than that of "12.5 plan" scenario, and after 2028, the total CO_2 emission shows a lower downtrend. In addition, it is noteworthy that, under the effect of improvement policies, economic growth speed of Liaoning Province may fall in between "WP mode" speed and "12.5 plan" speed to 2030 the GDP may amount to 6407.9 billion Yuan, lower than that of "WP mode" scenario, but 4.7% higher than that of "12.5 plan" scenario (Fig. 15).

These simulation results indicate that compared to "Twelfth Five-Year Plan" policies, the improved policies can achieve the same effects of CO_2 emission reduction, simultaneously can reduce greatly the negative influence to GDP and improve relatively the regional economic growth speed. This conclusion can be drawn obviously by comparison of CO_2 emission intensity: CO_2 emission intensity of "improvement" scenario not only reaches the promised of emission reduction target, but also becomes lower than that of "12.5 plan" scenario since 2021, and to 2030 it reaches 4.4% lower than that of "12.5 plan" scenario. Therefore, from the perspective of the integrated effects of regional economy development and CO_2 emission reduction, the "improvement" scenario is superior to "12.5 plan" scenario (Fig. 15).

10. Conclusion

Through comparative analysis of three simulation results of "WP mode", "12.5 plan" and "improvement" scenarios, some conclusions are drawn as follows:

(1) Through the improvement of emission reduction policies, the better effect of CO_2 emission reduction is achieved by less economic costs, the development of GDP and the non-fossil energy industries are greatly promoted, and the capacity of sustainable development of regional economy is enhanced. Therefore, the improved CO_2 emission reduction policies are superior to that in "Twelfth Five-Year Plan", and these improved recommendations can become some reference programs of future CO_2 emission reduction policies in Liaoning Province.
(2) Analysis of the typical case—Liaoning Province shows that, in the traditional industrial regions with large energy consumption per GDP and high CO_2 emission, through the elimination of laggard production capacity, special investment in technology and other measures, energy consumption per GDP can be rapidly reduced, industrial technology level can be improved, regional economy can keep benign development and the target of energy saving and emission reduction can be well realized. However, with the decrease of energy consumption per GDP, the adjustment of production capacity and technology may cause large economic losses and costs. Therefore, these policies are good measures of CO_2 emission reduction in short time, but not suitable for long-term implementation.
(3) Traditional industrial regions have relatively complete industrial system and strong economic strength, and this is conducive

to the development of non-fossil energy industries. Through direct investment in infrastructure construction by government, priority of land usage, low-interest loan, tax exemption, subsidy and so on, non-fossil energy industries development can be promoted. Therefore, these policies may become decisive and more effective ways of CO_2 emission reduction. However, due to the constraints of technology, capital, facility, acceptance extent of people, natural resource condition and other aspects, it is difficult to obtain a rapid effect of CO_2 emission reduction in short time and even may cause too large economic burden. Therefore, according to local situation, these policies are more suitable to be applied in a medium and long time when technology, facility and other conditions have a certain foundation.

(4) The EECP model is built based on the logical framework of CO_2 emission reduction policies and can well reflect the causal relationships of regional economic development, energy consumption, CO_2 emission and policy feedback effects. The model is used to simulate and control the material flow process of the system of "economy–energy–CO_2 emission-policies." Through comparatively analyzing the integrated effects of different scenarios, the regional CO_2 emission reduction policies are reasonably improved. Therefore, EECP model and its modeling thought have good practical application value in forecasting similar regional CO_2 emission trend, making and improving the policies of CO_2 emission reduction and energy development.

(5) Through the analysis in this study, traditional industrial regions with large CO_2 emission have the following specific characteristics: the economy system is industry-dominated; the proportion of laggard production capacity with large energy consumption is large; the fossil fuel accounts for more than 90% in the total energy consumption; it shoulders dual tasks of rapidly developing regional economy and largely saving energy and reducing CO_2 emission. Therefore, only the targeted CO_2 emission reduction policies are made and implemented, can the sustainable economic growth and the minimized CO_2 emission be realized.

Therefore, if studying from a national perspective, the specific characteristics of traditional industrial regions with large CO_2 emission may be averaged, and CO_2 emission reduction policies may be difficult to meet the requirements of regional development or achieve the more desirable effects. For example, from a national perspective, elimination of laggard production capacity may not achieve obvious benefits, and large investment in non-fossil energy industries in short time may be feasible, but not unscientific for the traditional industrial regions with large CO_2 emission. Moreover, a country's policy may not be suitable for another country, but the policies made for traditional industrial areas with large CO_2 emission is probably used for same types of areas.

Now, CO_2 emission reduction has becomes a global problem and the involved regions are varied, therefore, study of CO_2 emission reduction aiming at regional typological characteristic has more reference and application value compared to study from different spatial scales. Therefore, analysis of typological areas should become an important part in the study of future CO_2 emission reduction policies.

Acknowledgments

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Appendix A. The auxiliary results

See Appendix Table A1

Table A1
The variables and equations in VENSIM software.

(1) actual special investment in technology = adjustment polices of production capacity and technology*special investment in energy saving technology
(2) actual eliminated laggard production capacity = eliminated laggard production capacity * adjustment polices of production capacity and technology
(3) $z1 = 0.7143$
(4) $z2 = 1.4286$
(5) $z3 = 13.3$
(6) $p3 = 1\text{-}p1\text{-}p2$
(7) carbon emission coefficient $e3 = 5.95644*44/12$
(8) CO_2 emission amount1 = coal*carbon emission coefficient e1
(9) CO_2 emission amount2 = crude oil*carbon emission coefficient e2
(10) CO_2 emission amount3 = natural gas*carbon emission coefficient e3
(11) CO_2 emission intensity = total amount of CO_2 emission/GDP
(12) coal = fossil energy consumption amount*p1/z1
(13) crude oil = fossil energy consumption amount*p2/z2
(14) Effects of energy saving policy adjustment = (0.0715*(actual eliminated laggard production capacity 1ˆ−0.3489) + (2.4197* actual special investment in technology 1 + 14.624))/GDP
(15) eliminated laggard production capacity = INTEG (elimination increment,484.966)
(16) Elimination increment = (−20.321*Ln(Time-2005) + 112.63)
(17) Emission reduction target 1 = 2.41702
(18) Emission reduction target 2 = 2.2156
(19) Energy consumption amount = energy demand amount
(20) Energy consumption per GDP = natural trend of energy consumption per GDP-effects of energy saving policy regulation
(21) Energy demand amount = GDP *energy consumption per GDP
(22) Carbon emission coefficient $e1 = 0.539426*44/12$
(23) Fossil energy consumption amount = energy consumption amount-"non-fossil energy consumption amount"
(24) Wind energy increment = IF THEN ELSE("policies of promoting non-fossil energy" = 1, wind energy*wind energy increase rate1,wind energy*wind energy increase rate2)
(25) GDP increase rate = WITH LOOKUP (Time, ([(2009,0)-(2050,0.3)], (2009.25,0.146053), (2012.13,0.138158),(2014.39,0.125), (2016.65,0.106579),(2018.91,0.0907895), (2021.41,0.0684211),(2024.42,0.05), (2027.31,0.0355263),(2030.82,0.0236842), (2035.33,0.0144737),(2041.85,0.0105263), (2049.87,0.00526316)))
(26) wind energy increase rate2 = WITH LOOKUP (Time,([(2009,0)-(2050,2)], (2009,1.42806), (2009.75,0.938596),(2010.5,0.605263), (2011.51,0.350877),(2013.64,0.219298), (2016.4,0.140351),(2019.41,0.0964912), (2023.54,0.0614035),(2029.31,0.0438596), (2049.87,0.0350877)))
(27) GDP increment = GDP*GDP increase rate-actual eliminated laggard production capacity 1
(28) GDP = INTEG (GDP increment,15212.5)
(29) hydropower = INTEG (hydropower increment, 70.862)
(30) hydropower increase rate = WITH LOOKUP (Time,([(2000,0)-(2050,0.3)], (2005,0.261629), (2006,0.207374),(2006.57,0.156579), (2008,0.0741089),(2009.94,0.0421053), (2014.07,0.025),(2020.34,0.0144737), (2049.85,0.00789474)))
(31) hydropower increment = hydropower*hydropower increase rate

Table A1 (*continued*)

(32)	wind energy increase rate1= WITH LOOKUP (Time,([(2009,0)-(2050,2)], (2009,1.42806), (2009.75,0.842105),(2010.38,0.622807), (2011.13,0.464912),(2012.39,0.315789), (2014.27,0.201754),(2016.27,0.140351), (2019.03,0.0789474),(2022.54,0.0263158), (2029.19,0.022),(2049.62,0.012)))
(33)	investment increase rate=0.8447*power(Time-2008, −0.917)
(34)	investment increment=investment increase rate*special investment in energy saving technology
(35)	natural gas=fossil energy consumption amount*p3/z3
(36)	natural trend of energy consumption per GDP=WITH LOOKUP (Time,([(2000,0)-(2100,2)], (2006,1.54415),(2007,1.42145), (2008.1,1.2807),(2009.02,1.20175), (2009.94,1.12281),(2011.77,1.04386), (2014.07,0.973684),(2016.97,0.885965), (2020.8,0.807018),(2025.23,0.736842), (2029.66,0.692982),(2036.09,0.640351), (2043.27,0.605263),(2049.85,0.587719)))
(37)	"non-fossil energy consumption amount"=solar energy+nuclear energy+wind energy+hydropower
(38)	nuclear energy= INTEG (nuclear energy increment,0)
(39)	nuclear energy increment=IF THEN ELSE("policies of promoting non-fossil energy"=1, (IF THEN ELSE(Time=2012, 430.642 , (IF THEN ELSE (Time=2017, 430.642,0)))),nuclear power plant construction)
(40)	nuclear power plant construction=IF THEN ELSE(Time < 2033,430.642*PULSE TRAIN(2012, 1 , 5 , 2032),215.321*PULSE TRAIN(2027, 1 , 5 , 2042))
(41)	$p1$= WITH LOOKUP (Time, [(2005,0.5)-(2050,0.8)],(2005,0.73581), (2006,0.736842), (2007,0.754639),(2008.17,0.756579), (2008.99,0.72807),(2009.95,0.735526), (2010.64,0.74386),(2011.74,0.708772), (2013.12,0.701754),(2013.94,0.726316), (2014.91,0.687719),(2016.01,0.701754), (2016.7,0.670175),(2017.8,0.680702), (2019.04,0.649123),(2020.69,0.631579), (2023.03,0.642105),(2025.78,0.62807), (2029.91,0.57193),(2033.76,0.54386), (2037.75,0.533333),(2043.94,0.522807), (2050,0.51579))
(42)	$p2$= WITH LOOKUP (Time,([(2005,0)-(2050,0.8)], 2005,0.238596),(2006,0.250774), (2007,0.23299),(2008.17,0.23378), (2008.99,0.252632),(2010.09,0.25614), (2010.5,0.238596),(2011.47,0.242105), (2012.57,0.263158),(2013.67,0.277193), (2014.22,0.25614),(2015.05,0.273684), (2016.7,0.280702),(2018.07,0.259649), (2019.86,0.280702),(2022.2,0.263158), (2024.54,0.287719),(2026.74,0.280702), (2029.36,0.308772),(2050.14,0.326316)))
(43)	Carbon emission coefficient $e2$=0.83632*44/12
(44)	"policies of promoting non-fossil energy"=IF THEN ELSE (policy making=1, 1 ,2)
(45)	policy making=IF THEN ELSE(CO_2 emission intensity-emission reduction target 1 > 0, 1 , (IF THEN ELSE(CO_2 emission intensity-emission reduction target 2 > 0, 0.5,0)))
(46)	"proportion of non-fossil energy"="non-fossil energy consumption amount"/energy consumption amount*100
(47)	adjustment polices of production capacity and technology=DELAY1I (IF THEN ELSE(policy making > 0.5, 1,IF THEN ELSE(policy making > 0, 0.5, 0)),2 , 1)
(48)	wind energy= INTEG (wind energy increment, 75.9129)
(49)	solar energy= INTEG (solar energy increment, 0.00239139)
(50)	solar energy increase rate1=10.506*EXP(-0.5001*(Time-2009))
(51)	solar energy increase rate2= WITH LOOKUP (Time,([(2009,0)-(2100,20)], (2008.87,12.7193), (2009.75,11.4912),(2010.25,7.98246), (2010.63,6.31579),(2011.38,4.5614), (2012.13,2.54386),(2013.14,1.22807), (2014.01,0.701754),(2015.96,0.350877), (2019.3,0.175439),(2049.75,0.06)))
(52)	solar energy increment=IF THEN ELSE("policies of promoting non-fossil energy"=1, solar energy*solar energy increase rate1 , solar energy*solar energy increase rate2)
(53)	special investment in energy saving technology= INTEG (investment increment, 9.64108)
(54)	total amount of CO_2 emission=CO_2 emission amount1+CO_2 emission amount2+CO_2 emission amount3

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